SEARCHES FOR NEW PHYSICS AT THE TEVATRON

V. BÜSCHER

Universität Mainz, Institut für Physik, Staudinger Weg 7,
55099 Mainz, Germany

Recent results of searches for new phenomena using data collected in Run I by the CDF and D0 experiments are presented. D0 set limits for top squarks decaying into b$l\tilde{\nu}$ significantly beyond the reach of previous analyses in this channel ($m_{\tilde{t}} > 140$ GeV at 95% C.L. for $m_{\tilde{\nu}} = 45$ GeV). CDF exclude top squarks decaying into bτ for masses below 111 GeV. In addition, D0 have analyzed photon and electron pair production to search for effects of large extra dimensions. No evidence is found, resulting in limits on the effective Planck scale of 1.1 TeV. Finally, D0 have used a model-independent search strategy for new physics at high $p_\perp$ to test more than 32 different final states for evidence of a signal. Observations in all samples are found to be consistent with expectations from the Standard Model.

1 Introduction

With the end of Run I in 1996 the two Tevatron experiments CDF and D0 each had collected about 110 pb^{-1} of p$\bar{\text{p}}$-collision data. Since then both collaborations have been preparing upgrades of their detectors that will allow to operate them during the next run of the upgraded Tevatron (Run II). For Run II, 3-4 fb^{-1} of data are expected in the first few years of running.

The Run I data have been analyzed extensively in search for new physics by both experiments. New results from four analyses are presented here. In addition, the sensitivity expected in these channels for Run II is discussed.

2 Searches for Supersymmetry

Supersymmetry predicts new supersymmetric degrees of freedom for each Standard Model particle field. The scalar supersymmetric fields associated with the left- and right-handed fermion fields can mix to form mass eigenstates, potentially generating relatively light scalar particles, in particular in the third generation. It is therefore of interest to search for the production of

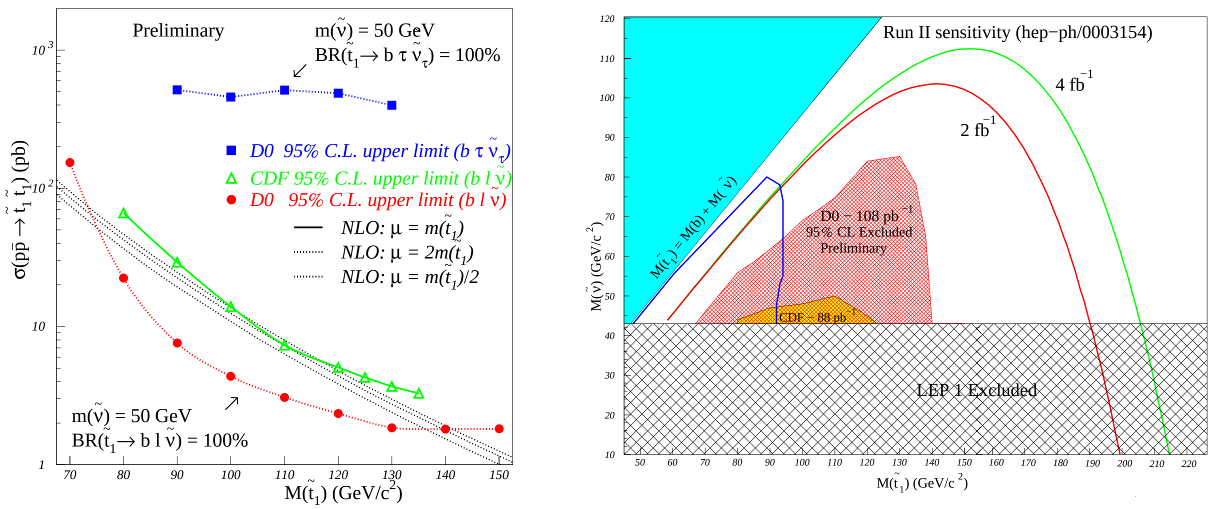

Figure 1: Limits on the pair production cross section of top squarks decaying into $\mathrm{bl}\tilde{\nu}$ with $m_{\tilde{\nu}} = 50$ GeV in comparison with the MSSM expectation (left); Regions in $m_{\tilde{\nu}}$ versus $m_{\tilde{\mathrm{t}}}$ excluded by D0 (this analysis), CDF [3] and LEP [4] (right). The sensitivity expected for Tevatron Run II [5] is plotted for integrated luminosities of 2 fb^{-1} and 4 fb^{-1}.

light stop quarks at the Tevatron. Both D0 and CDF have extended previous analyses with new searches for top squarks: D0 are presenting a new search within the Minimal Supersymmetric Standard Model (MSSM), CDF have analyzed their data in search for top squarks in Supersymmetry with R-parity violation.

In $\mathrm{p\bar{p}}$-collisions top squarks are pair-produced strongly via $\mathrm{q\bar{q}}$-annihilation or gluon-gluon-fusion. Cross-sections have been calculated to next-to-leading order [1] and are of the order of 10 pb for $m_{\tilde{\mathrm{t}}} = 100$ GeV.

2.1 Top Squarks in the MSSM

Within the MSSM, top squarks that are light enough to be observed at the Tevatron decay primarily into $\mathrm{b}\tilde{\chi}^{+}$ (if $m_{\tilde{\mathrm{t}}} > m_{\mathrm{b}} + m_{\tilde{\chi}^{+}}$), $\mathrm{bff}\chi_1^0$, $\mathrm{c}\chi_1^0$ or $\mathrm{bl}\tilde{\nu}$. The latter decay mode is dominant for light sneutrinos and would lead to final states containing two b-jets, two leptons and missing transverse energy from sneutrinos escaping detection. D0 have searched for pair production of top squarks in this channel in final states containing one electron and one muon, as backgrounds in this mode are particularly small.

Based on a previous analysis [2] of the final state $\mathrm{e}\mu$ $\not{E}_{\mathrm{t}} + X$, events are selected if they contain one isolated electron and muon with $p_{\perp} > 15$ GeV and missing transverse energy of at least 20 GeV. The electron and muon are required to be central and acoplanar to suppress background from $\mathrm{Z} \to \tau^{+}\tau^{-}$ and QCD. After all cuts, 13.4 ± 1.5 events are expected within the Standard Model. Typical signal efficiencies range from 0.5% ($m_{\tilde{\mathrm{t}}} = 100$ GeV, $m_{\tilde{\nu}} = 70$ GeV) to 4.0% ($m_{\tilde{\mathrm{t}}} = 140$ GeV, $m_{\tilde{\nu}} = 40$ GeV).

In the D0 data 11 events are selected and therefore no evidence of signal is observed. From this, upper limits on the top squark pair production cross section have been derived at 95% C.L. (Fig. 1). Assuming $\mathrm{BR}(\tilde{\mathrm{t}} \to \mathrm{lb}\tilde{\nu}) = 1$, this limit corresponds to an excluded region in the $(m_{\tilde{\mathrm{t}}}, m_{\tilde{\nu}})$-plane as indicated in Fig. 1, significantly improving on existing limits from LEP [4] and CDF [3].

The expected sensitivity for Run II has been estimated for this channel using a MC study [5]. Due to the high luminosity at an increased center of mass energy (2 TeV), the reach of this analysis will be extended considerably beyond the limit presented here: top squark masses of

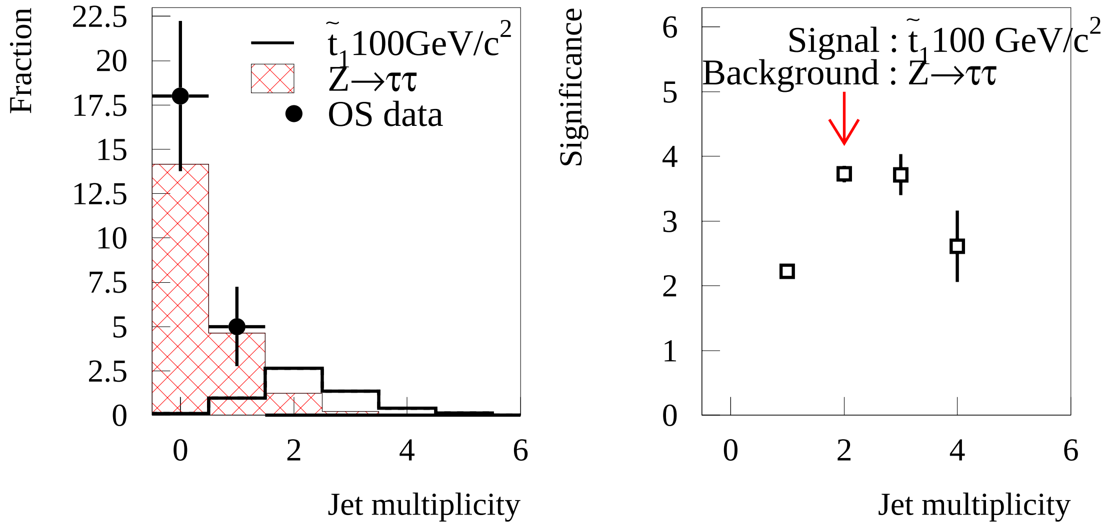

Figure 2: Number of reconstructed jets in the search for $\tilde{t} \rightarrow b\tau$ for the signal, background from $Z \rightarrow \tau\tau$ and data (left); The expected significance of a top squark signal is maximized by requiring at least two jets (right).

200 GeV and beyond will be accessible for sneutrino masses around 50 GeV (Fig. 1).

2.2 Top Squarks with R-Parity Violation

The most general superpotential W contains a number of terms that lead to violation of lepton- or baryon-number and that are generally removed by imposing the conservation of R-parity:

$$\begin{aligned} W &= W_{RPC} + W_{TRPV} + W_{BRPV} \\ &= \bar{U} y_u Q H_u - \bar{D} y_d Q H_d - \bar{E} y_e L H_d + \mu H_u H_d + \\ &\quad \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k + \\ &\quad \epsilon_i L_i H_u \end{aligned} \tag{1}$$

Here U, D, Q and L, E denote the quark and lepton superfields, μ is the Higgsino mass parameter and y contain the Yukawa couplings. The first 4 terms (W_{RPC}) do not violate R-parity conservation and generate the standard MSSM lagrangian. In addition there are 45 trilinear couplings λ_{ijk} and 3 bilinear couplings ϵ_i (with generation indices i,j,k).

Both trilinear (λ'_{333}) and bilinear (ϵ_3) terms can generate a tree-level coupling between top squark, b quark and τ lepton. Therefore, when considering models without the conservation of R-parity, the additional decay mode $\tilde{t} \rightarrow b\tau$ has to be taken into account and can even dominate if the decay into chargino is kinematically not accessible.

Top squark pair production in this scenario leads to final states containing two tau leptons and two b quarks. This signature has been considered in a previous search for third generation leptoquarks[6], requiring one tau to decay hadronically, the other leptonically to an electron. The CDF collaboration has reoptimized their previous analysis after improvements in the identification of hadronic tau decays, which has been enhanced by using tracking information as well as π_0-reconstruction. To minimize the dependency on the MC modelling of the tau identification (as well as to cancel other systematic errors), the number of signal-like events is measured relative to a measurement of the $Z \rightarrow \tau\tau$ cross section. Rejecting events with one or more jets in

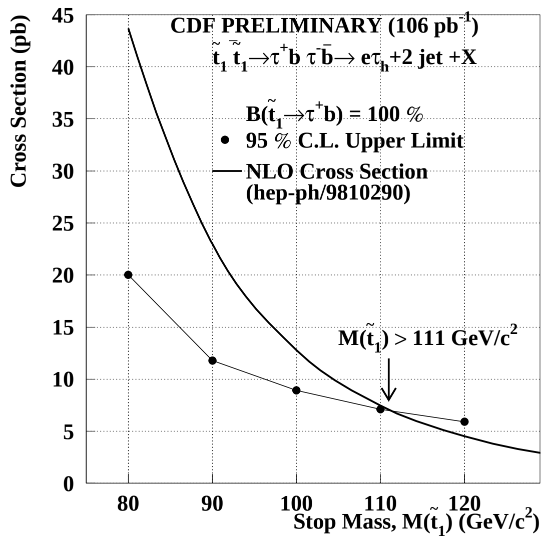

Figure 3: Limit on the top squark pair production cross section for $\tilde{\mathrm{t}} \to \mathrm{b}\tau$ in comparison with the cross section expected within the MSSM. Top squark masses below 111 GeV are excluded at 95% C.L.

the final state, 48 ± 8 events from $\mathrm{Z} \to \tau\tau$ are selected in the data. In contrast to this, two jets or more are required to select events from top squark pair production (Fig. 2). This and other signal cuts have been chosen to maximize the significance for $m_{\tilde{\mathrm{t}}} = 100$ GeV.

After all cuts signal events are selected with an efficiency of 1.6% for $m_{\tilde{\mathrm{t}}} = 100$ GeV. No events are observed in the data, consistent with the expectation of $1.91 \pm 0.11(stat) \pm 0.15(syst)$ from Standard Model backgrounds. Fig. 3 shows the limit on the top squark pair production cross section derived from this observation after normalization to the $\mathrm{Z} \to \tau\tau$ cross section. Based on the NLO cross section calculation, top squarks lighter than 111 GeV can be excluded at 95% C.L. for $\mathrm{BR}(\tilde{\mathrm{t}} \to \mathrm{b}\tau) = 1$.

3 Search for large extra dimensions

In models with large extra dimensions[7], the effective Planck scale M_S can be as low as $O(1\,\mathrm{TeV})$, which would be close enough to the weak scale to have considerable impact on the hierarchy problem. Effects from large extra dimensions can be observed at high energy colliders via direct production of gravitons as well as via anomalous difermion or diboson production proceeding through virtual graviton exchange (Fig. 4).

D0 have searched for virtual graviton effects in dielectron and diphoton production, taking into account both the invariant mass M and the production angle $\cos\theta$ of the system. The

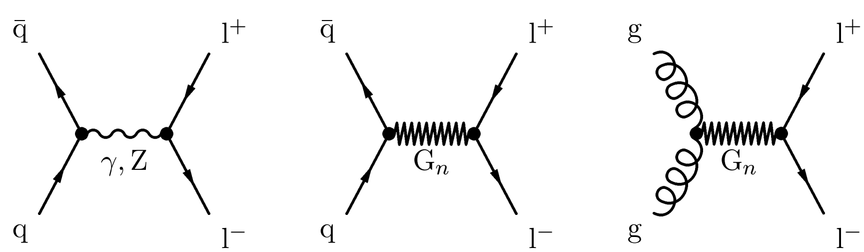

Figure 4: Feynman diagrams contributing to dilepton production in $\mathrm{p\bar{p}}$-collisions for models with gravitons G_n allowed to propagate in large extra dimensions.

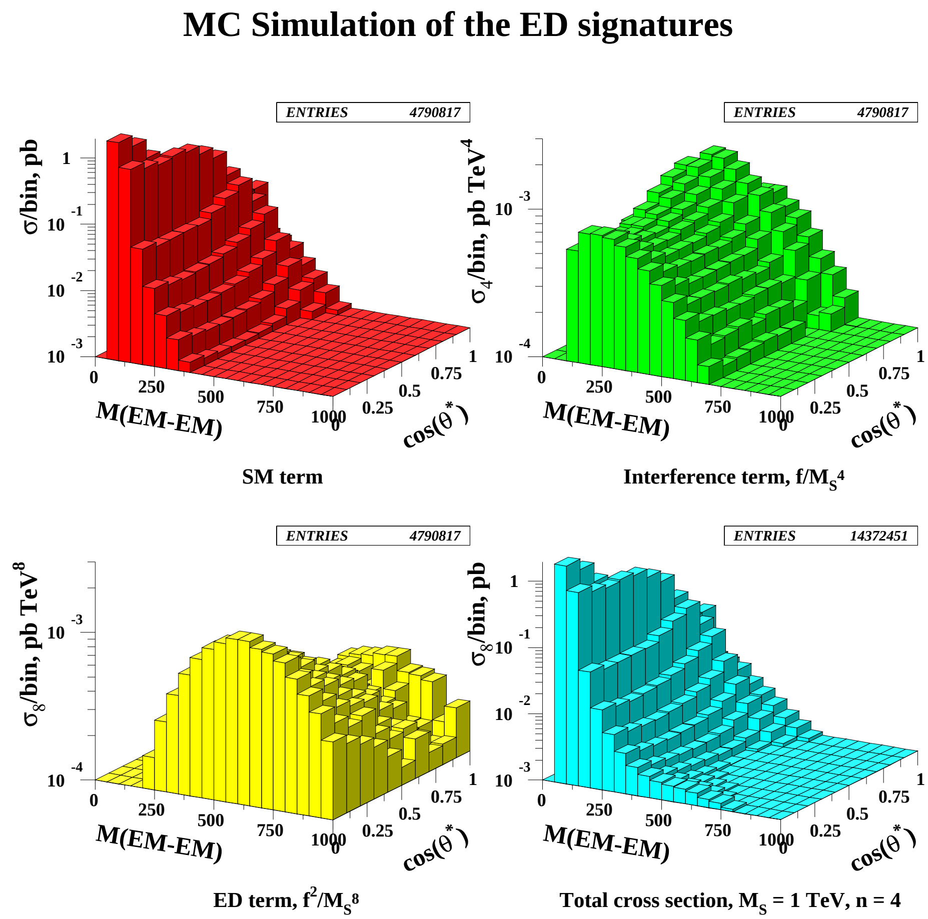

Figure 5: Di-EM cross section as a function of di-EM mass M and production angle θ^* for the Standard Model term (top left), interence term (top right), Kaluza-Klein term (bottom left) as well as the sum of all terms (bottom right).

differential cross-section in the presence of large extra dimensions is modified by contributions from Kaluza-Klein towers of graviton states and can be parametrized as

$$\frac{d^2\sigma}{d\cos\theta^* dM} = \frac{d^2\sigma_{SM}}{d\cos\theta^* dM} + \eta_G f_{int}(\cos\theta^*, M) + \eta_G^2 f_{KK}(\cos\theta^*, M), \tag{2}$$

with an interference term f_{int}, a pure Kaluza-Klein term f_{KK} and a model-dependent constant η_G containing the dependence on M_S and the number of extra dimensions. Fig. 5 demonstrates the difference in shape comparing both f_{int} and f_{KK} to the Standard Model cross section.

Since the Standard Model background from misidentified electrons or photons at high invariant masses is negligible, very loose identification cuts have been applied in this analysis. In particular, no tracking information is used, thereby effectively treating both photons and electrons as EM objects. Requiring two isolated EM objects, about 80% of the signal events pass the selection. Efficiencies are calculated with Graviton-induced effects as implemented in a MC generator at leading order. Higher order effects are partially modelled by adding a transverse momentum to the di-EM system, based on the transverse momentum spectrum of di-EM events observed in the data.

Backgrounds are entirely dominated by Drell-Yan and direct diphoton production, with only small contributions from instrumental backgrounds (Fig. 6). The data are consistent with

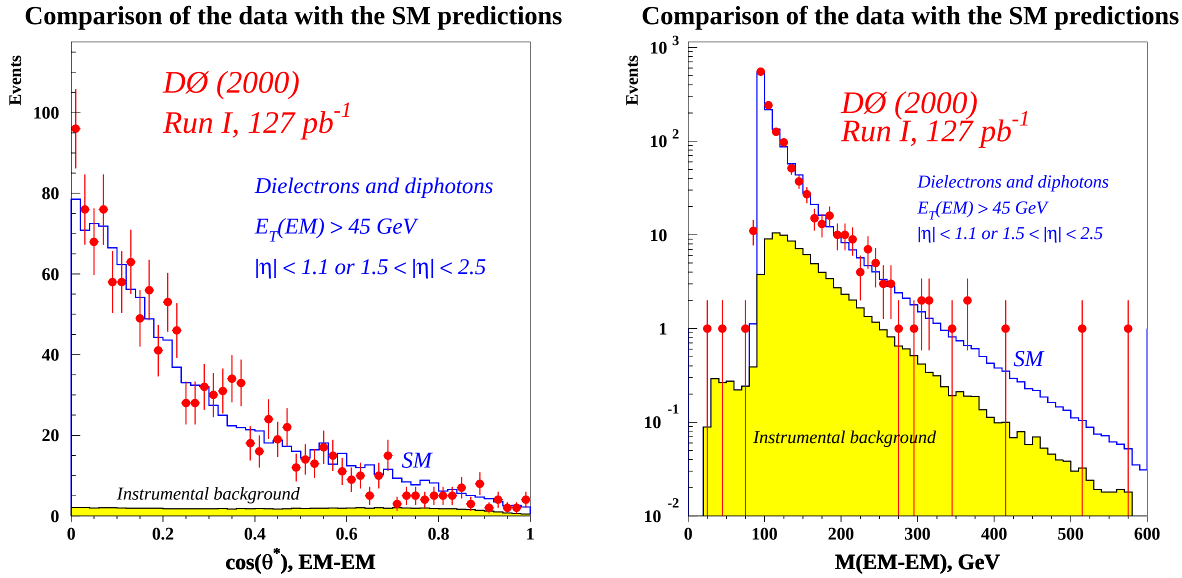

Figure 6: Distribution of di-EM production angle θ^* (left) and di-EM invariant mass M (right) for D0 data (dots) and expectations from the Standard Model (open histogram); Contributions from instrumental backgrounds are displayed as the solid histogram.

the expectations for di-EM production from Standard Model sources throughout the entire $(M, \cos\theta)$-plane. Therefore, a fit to the data of Equation 2 yields a value for η_G consistent with zero, limiting the contribution from virtual graviton corrections to $\eta_G < 0.46\,\mathrm{TeV}^{-4}$ at 95% C.L. This result can be translated into a lower limit on the effective Planck scale within a particular model of large extra dimensions. For instance, using the formalism introduced by Hewett [8], M_S is found to be larger than 1.1 TeV at 95% C.L., comparable to current limits from LEP2 [9]. Extrapolating the D0 results to the Tevatron Run II [10], effective Planck masses in the range of 1.5 to 2.5 TeV are expected to be probed with integrated luminosities of the order of 2 fb^{-1}.

4 Model-independent Searches

Both CDF and D0 have published searches for a large number of final states and numerous models of new physics beyond the Standard Model. While this is aimed at an optimal sensitivity for the particular models considered in these searches, a more systematic approach seems appropriate to ensure that no signal has been missed. In this context D0 have developed a method to automatically find a significant excess of data at high $p_\perp$ with respect to the Standard Model expectation [11]. This method has now been applied to 32 different final states to test the full D0 Run I data sample for hints of physics beyond the Standard Model.

Briefly, the method proceeds in the following steps (for details the reader is referred to [11]): after splitting the dataset into various exclusive final states, the d-dimensional space of variables to be considered is mapped into a d-dimensional unit-box such that the background distribution is flat. Regions of interest at high $p_\perp$ are defined in the unit-box, and for each region, the probability R that the expected background fluctuates to or above the number of events seen in the data is calculated. After scanning all possible regions for small values of R, the significance P of observing values as small as the minimum R is calculated using a set of MC experiments that are subjected to the exact same procedure as the data.

The final states considered in the D0 data include: eμX, W+jets, e$\not{E}_t$+jets, Z+jets, ee+jets, $\mu\mu$ + jets, l/γ l/γ l/γ X, Wγ as well as dijets. Standard and well-understood criteria are used

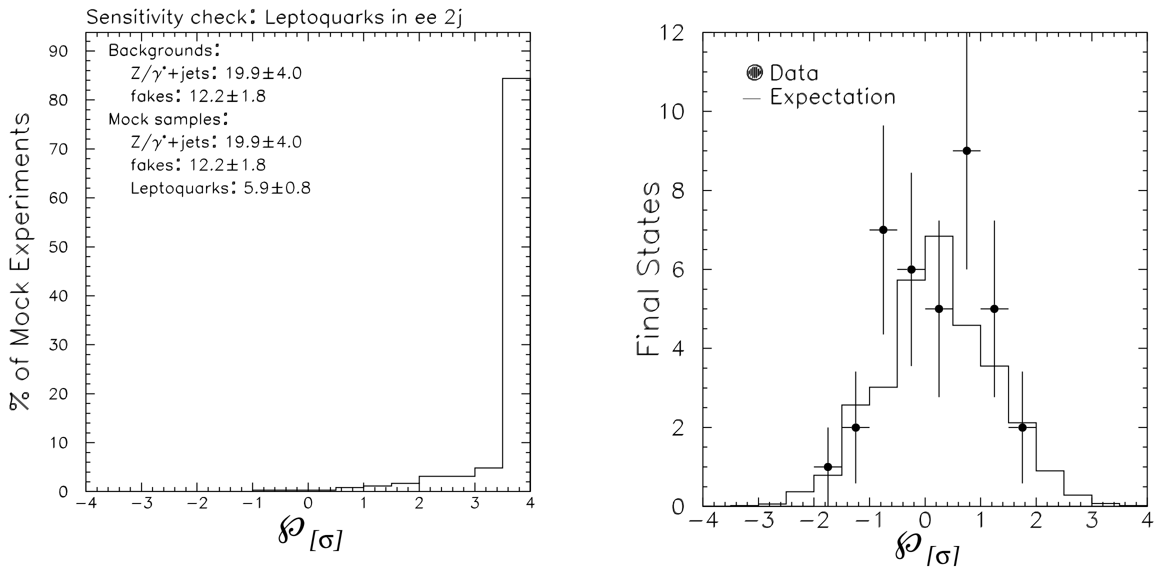

Figure 7: Distribution of significance P (see text) for MC experiments containing a signal from leptoquark pair production (left) and for all final states considered in D0 data in comparison with expectations from Standard Model MC (right).

for reconstruction and identification of electrons, photons, muons, jets and $\not\!\!E_{\rm t}$. Depending on the final state, the variables used in the method are $\not\!\!E_{\rm t}$, the $p_\perp$ of reconstructed leptons, jets and vector bosons (W and Z bosons are reconstructed from leptons and the missing $E_{\rm t}$ vector).

To check whether the method is sensitive to a high-$p_\perp$ signal in the data, fake data samples have been generated adding events from pair production of first generation leptoquarks ($m_{LQ}=$ 170 GeV). Fig. 7 shows the distribution of the significance P as measured in 100 such MC experiments. In about 90% of the experiments evidence for signal is found at a significance of more than 3σ.

Applying the method to the D0 Run I dataset, the significance P is calculated for the full list of final states described above. Fig. 7 shows the distribution of P in comparison with the expectation from background MC experiments. The data are in good agreement with the Standard Model, therefore no evidence for a significant excess has been observed.

5 Summary

Recent results of searches for new phenomena using data collected in Run I by the CDF and D0 experiments have been presented. Both collaborations have expanded their searches for evidence of supersymmetry with new analyses on the production of top squarks. D0 set a limit for top squarks decaying into bl$\tilde{\nu}$ significantly beyond the reach of previous analyses in this channel (e.g. $m_{\tilde{t}}>140$ GeV at 95% C.L. for $m_{\tilde{\nu}}=45$ GeV). CDF exclude top squarks decaying into bτ for masses below 111 GeV. In addition, D0 have analyzed photon and electron pair production to search for effects of large extra dimensions. No evidence was found, resulting in limits on the effective Planck scale of 1.1 TeV. Finally, D0 have used a model-independent search strategy for new physics at high $p_\perp$ to test more than 32 different final states for evidence of a signal. Observations in all samples are found to be consistent with expectations from the Standard Model.

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